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DEVELOPMENT AND EVALUATION OF ALUMINUM-GRAPHITE FINE WIRE AND STRIP (RIBBON)

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FINAL TECHNICAL REPORT

NAVAL SEA SYSTEMS COMMAND

DEVELOPE AND EVALUATE ALUMINUM-GRAPHITE FINE WIRE AND STRIP (RIBBON)

12 JANUARY 1976

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FOREWORD

This final technical report covers the work performed under Contract No. N00024-75-C-5067 from 10 January 1975 through 10 November 1975. This contract with Fiber Materials, Incorporated was issued by the Department of the Navy, Naval Sea Systems Command. The work has been administered under the technical direction of Mr. Marlin A. Kinna, Naval Sea Systems Command, Washington, D.C.

The program was directed by Dr. Roger T. Pepper as Program Manager. Assisting as project engineers were Mr. Thomas A. Zack and Mr. Daniel C. Nelson.

FINAL TECHNICAL REPORT

CONTRACT NO. N00024-75-C-5067

Develop and Evaluate Aluminum-Graphite Fine Wire and Strip (Ribbon)

1. SUMMARY:

The program objective was to develop and evaluate aluminum-graphite fine wire and strip (ribbon) in connection with efforts to provide high strength, lightweight, temperature resistant materials for rocket motor cases and third stage components of strategic missile systems.

In the first phase of the program, parameters of the Lachman Process were optimized in the Chemical Process Laboratory at FMI, and fine aluminum-graphite wire was successfully formed at speeds approaching 60 inches per minute. No unwetted fibers were apparent in the metallographic studies performed on the wire, nor were voids noticed as in the case of the eight strand wire produced in previous experimental work. Technology for the process was transferred to Materials Concepts, Inc. (FMI's metal-graphite composite manufacturing facility) where 8000 feet of single strand Thornel 50/A201 aluminum-graphite wire was prepared for the second and third phases of the program.

The study continued to develop a strip-forming process (Phase 2 and 3) by coupling it directly with the Lachman Wetting Process. Graphite fibers were successfully infiltrated under experimental conditions in FMI's Chemical Process Laboratory using an open melt with a continuous argon blast preventing oxidation of the fiber coating prior to drawing it through the aluminum. By installing a roller system in the melt area, a continuous strip of reasonably constant area was obtained using 8 strands and 16 strands of Thornel 50 fibers.

Maximum strip size using 16 strands of T-50 was 0.25" x 0.015". Work using this approach led to an aluminum-graphite prepreg strip consisting of 110 Ksi tensile strength and 21 Msi modulus at 32 volume percent fibers, which is comparable to the properties of previously prepared eight strand aluminum-graphite wire.

The program objective of continuously making 0.5 inch wide aluminum-graphite strip was not obtained, and further development work will be required before the strip casting process will reach the manufacturing scale-up stage.

2. OBJECTIVES:

Phase 1) Develop fine aluminum-graphite wire (0.010 inches diameter).

Phase 2) Establish technology for the continuous casting of aluminum-graphite composite strip directly from the melt.

Phase 3) Develop an aluminum-graphite prepreg strip containing aligned multiple graphite fiber strands having 150,000 psi tensile strength and 30 million psi modulus at 40 volume percent fibers.

3. INTRODUCTION:

The high strength and stiffness to density ratios and high temperature capability of aluminum-graphite composites make them ideal materials for the motor cases and third stage components of strategic missile systems.

A potentially low-cost liquid metal infiltration process has been developed at FMI for continuously producing aluminum-graphite composite wire. A 0.05 inch diameter wire is currently being made in an experimental pilot plant on a 24-hour per day basis at Materials Concepts, Inc. using a commercially available high performance rayon precursor graphite yarn and conventional aluminum alloys. On a strength and stiffness to density ratio basis, the composite material is 1.3 and 3 times better, respectively, than currently available titanium alloys.

It is well known that aluminum does not readily wet graphite, and a surface treatment is necessary to promote this phenomenon. The titanium/boron deposition process described in the U.S. Patent No. 3,860,443 (Fiber Materials, Inc.) succeeds in coating the graphite fibers to promote wetting and also protects the fiber from surface degradation caused otherwise by excessive aluminum-carbide formation.

The aluminum-graphite fine wire and strip program sponsored by the Naval Sea Systems Command and conducted technically by Fiber Materials, Incorporated, was directed towards the development of high strength, low density materials for future use in the manufacture of complex shapes and large diameter cylindrical structures. The currently available 0.05 inch diameter, 11,500 fiber wire prepreg has a minimum bend radius of six inches, which is too large to negotiate the small radii to be encountered in the fabrication of complex multifiber orientation shapes such as hat section stiffeners, brackets, and knuckle joints of truss structures. Smaller diameter aluminum-graphite wire and thin strips have a significantly smaller bend radius, and should be more suitable for the fabrication of such complex shapes.

Irregularities in wire diameters due to processing methods make the fabrication of complex shapes more difficult than with a uniform material, and misalignment of Al-Gr wires often cause fiber breakage during fabrication due to excessive pressure at the wire cross-over areas. This affects the ultimate properties of the composite material, and also contributes to the excessive time necessary in packing wires and fabricating shapes. The development of uniform strip preform materials will resolve these problems.

Larger sizes of composite prepreg strip with the proposed rectangular cross-sections should be amenable to the achievement of high packing densities during

fabrication resulting in high fiber contents and high component strength and stiffness to density ratios.

Low-cost polyacrylonitrile (PAN) and pitch precursor multi-fiber graphite materials are becoming available commercially. For example, 30 million psi modulus PAN precursor graphite yarn is currently available at $38 per pound, and a low-cost pitch precursor graphite yarn of 30 million psi modulus and 300,000 psi tensile strength will be available in the future. Further reductions in fiber cost are anticipated as the market volume increases, which will lead to the production of low-cost aluminum-graphite composites. The wire and strip developments of tnis program will be equally compatible for use of these low-cost fibers when they are commercially available.

4. EXPERIMENTAL TECHNIQUES:

4.1 Process Techniques

4.1.1 Fine Wire Formation

The first phase of the program concentrated on the development of a fine aluminum-graphite wire using single strand Thornel 50 fiber and an A201 aluminum alloy. Modifications of the equipment previously used to make the 8 strand wire were employed to handle the single strand tow.

The infiltration equipment depicted schematically in Figure 1 consists of the following: (1) a supply reel to furnish a continuous roll of fiber, (2) a three zone Lindberg horizontal furnace for the CVD coating of titanium boride, (3) a Lindberg retort furnace for melting the aluminum alloy, (4) the A201 melt, and (5) a take-up reel for the composite wire. An actual picture of the equipment set-up has also been included (Figure 2).

The graphite fiber is treated by the reduction of boron and titanium chlorides with zinc vapor, thus depositing titanium and boron onto the fiber surfaces.

CONTINUOUS PROCESS FOR ALUMINUM-GRAPHITE COMPOSITE WIRE

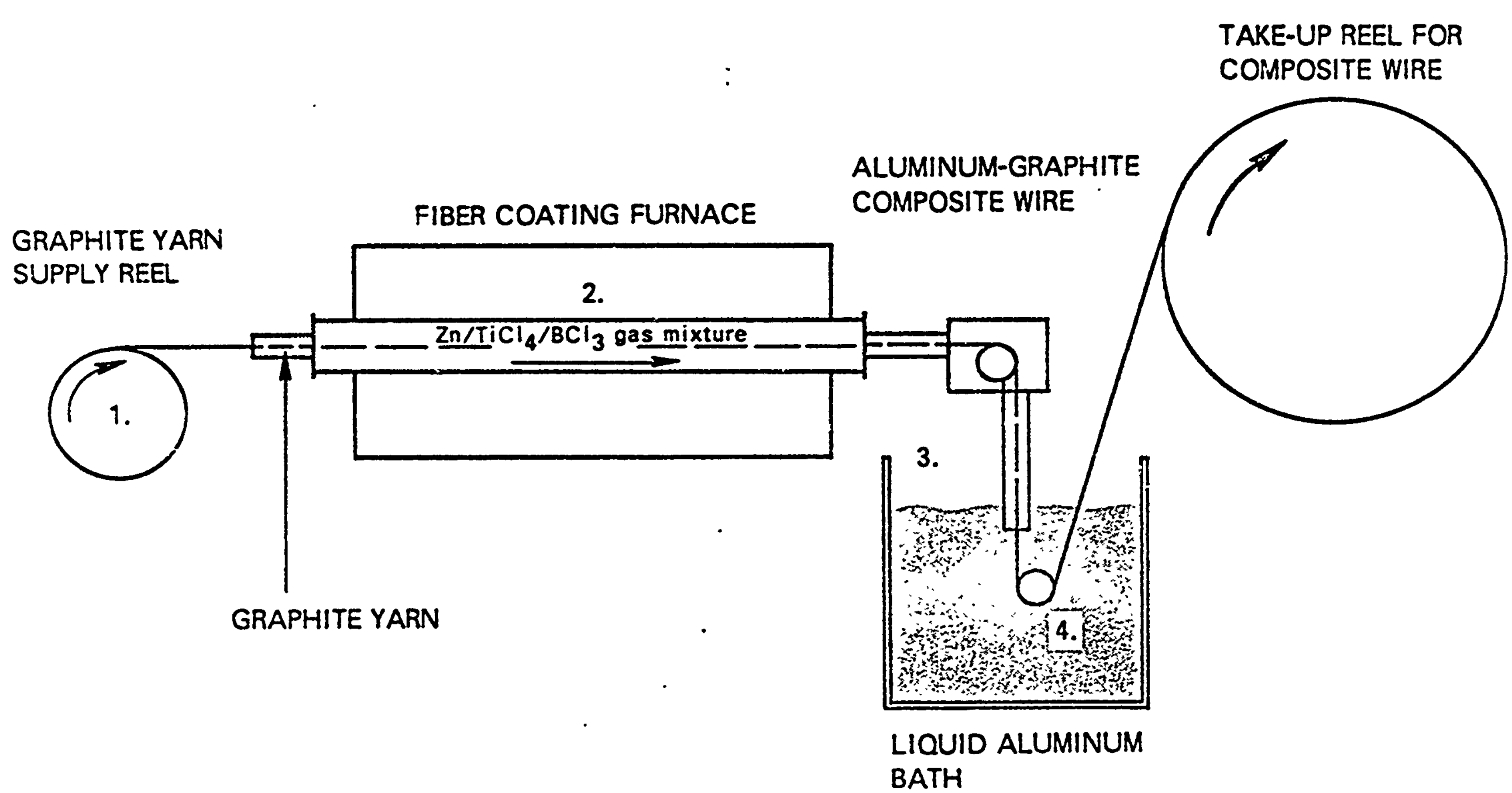
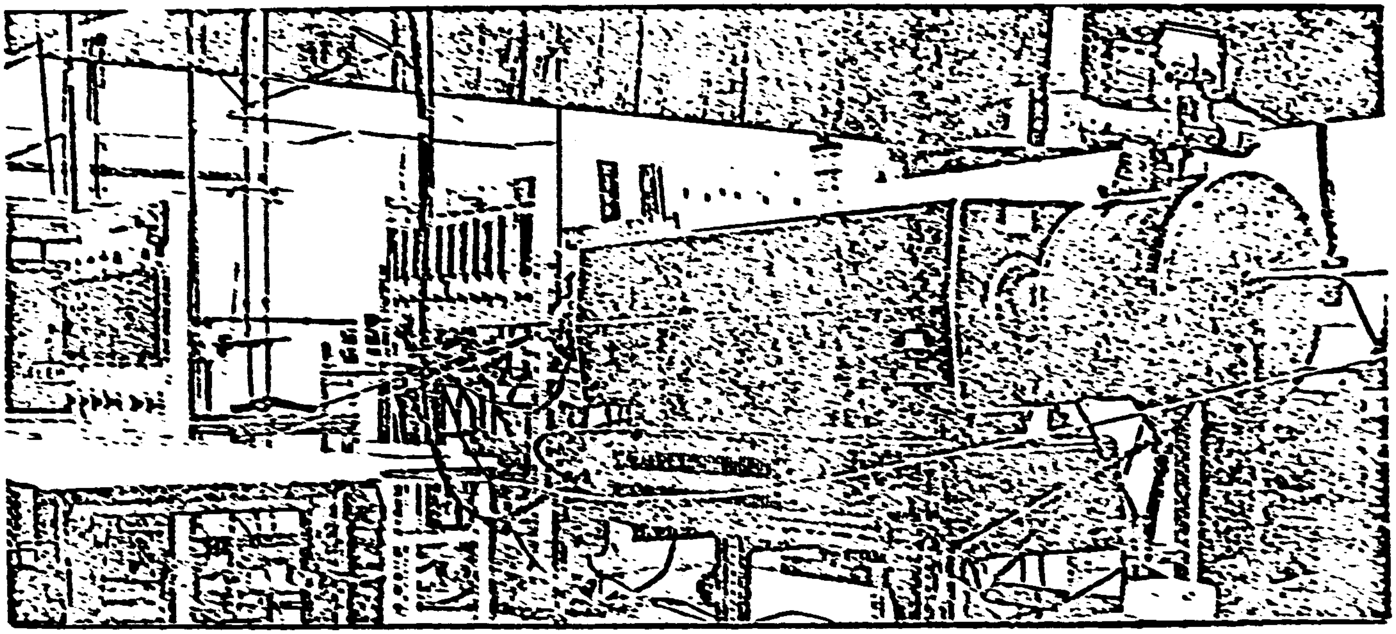


Figure 1

PROCESS EQUIPMENT FOR ALUMINUM-GRAPHITE

COMPOSITE WIRE/STRIP



OPEN MELT RETORT FURNACE

WITH STRIP-FORMING EQUIPMENT

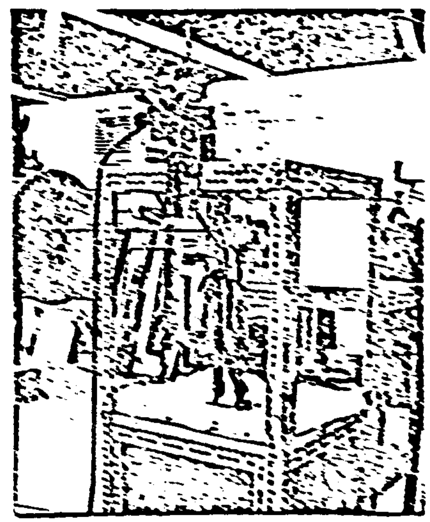


Figure 2

The gas mixture alters the fiber surface characteristics, and serves a dual purpose of promoting wetting by aluminum and protecting the T50 graphite fibers from reaction and degradation.

By optimizing coating parameters for the preparation of fine wire, both mechanical properties and operating speeds of the wire were increased significantly.

Fiber contents ranging between 38 and 43 volume percent were controlled by the operating speed, back tension on the yarn, and aluminum melt temperature. Optimum conditions were 30-60 inches per minute, three pounds, and 660°C respectively. The technology required to produce fine aluminum-graphite wire of 160,000 psi tensile strength at 38-43 volume percent fibers was transferred to MCI, where 8000 feet of fine wire was prepared for the following phase. A summary of the wire improvements during the program can be seen in Table 1.

4.1.2 Strip Formation

The second and third increments of the program were directed towards establishing technology for the continuous infiltration of aluminum-graphite composite strip directly from the melt. Initial work was performed on the previously prepared wire to form a ribbon or strip by drawing the wire through an aluminum melt, and forming it into the required shape during resolidification. Later efforts concentrated on forming strip directly from the infiltrating melt. A brief summary of different strip-forming processes appears in Table 2, and a list of property results have been accumulated in Table 3.

Several methods were used in preparing the strip during resolidification, each meeting with varying success. A pictoral representation in Table 4 of some strip samples produced demonstrates development of more consistent shapes by improvements in the forming process. For example, in experiment Z-70, a single argon jet was installed near the melt line (Figure 3) and a high gas flow was

Table 1

FINE WIRE PROGRESS CHART

SINGLE STRAND THORNEL 50/A-201 ALUMINUM ALLOY

WIRE PROPERTIES EXPERIMENT NO.	Z-44	Z-45	Z-48	OPTIMUM PROPERTIES
Operating Speed (in/min)	12	24	30	60
Linear Density (g/cm x 10^{-3})	2.8	2.38	2.4	2.30
Cross-Sectional Area (in^2 x 10^{-4})	1.31	1.60	1.60	1.55
Diameter (inches)	.016	.014	.014	0.13
Volume Percent Fiber	35	41	41	43
Breaking Load (lbs.)	17.4	22.6	25	27
Tensile Strength (psi)	96,200	140,000	156,000	174,000
Theoretical Tensile Strength (psi, rule-of-mixtures)	107,500	126,000	126,000	131,000
Calculated Tensile Strength as a Percentage of Rule-of-Mixtures	90	111	123	132

Approximate No. of Fibers 1440
Average Wire Density .0839 lb./in^3

Table 2

SUMMARY OF STRIP-FORMING PROCESSES

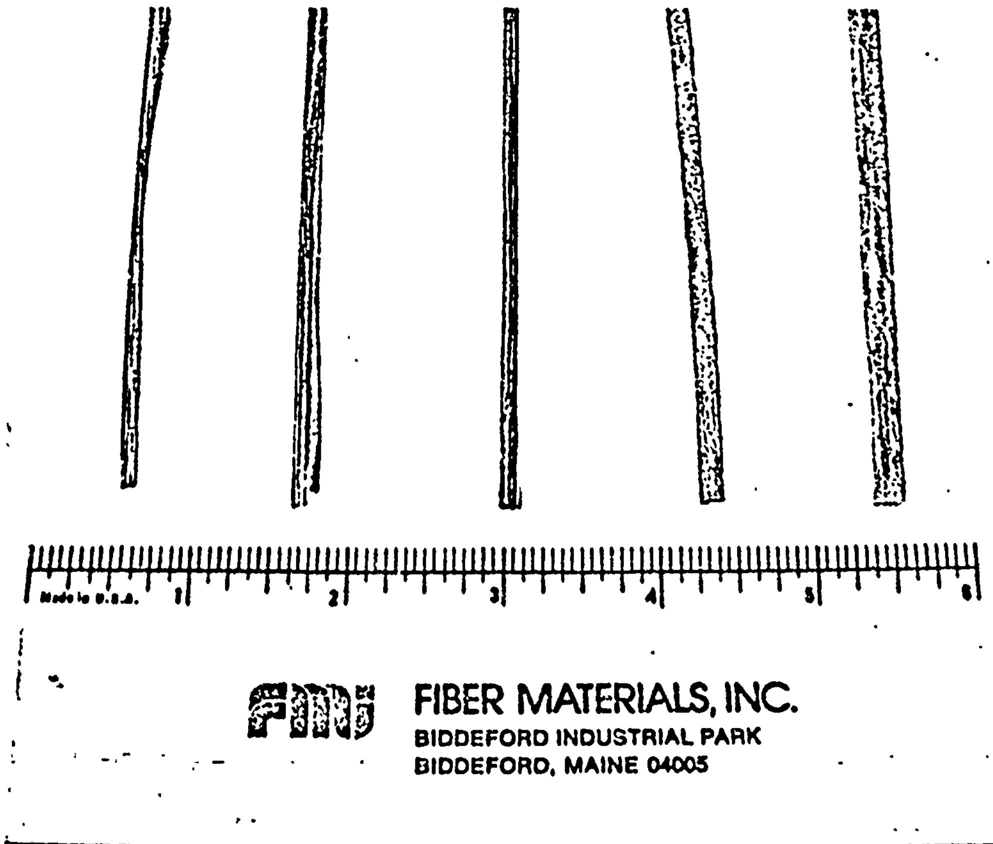
EXPERIMENT	STARTING MATERIAL	FORMING TECHNIQUES	RESULTS
Z-70	T-50/A201 Al/Gr Wire	Resolidification in A201 melt and strip forming by single argon jet	No meaningful test samples made
Z-71	T-50/A201 Al/Gr Wire	Resolidification in A201 melt and strip forming by two opposing argon jets	No meaningful test samples made
Z-72	T-50/A201 Al/Gr Wire	Resolidification in A201 melt and strip forming by drawing through die	No meaningful test samples made
N-1-2	T-50 Fiber	Direct strip formation from A201 melt using two opposing argon jets	Inconsistent shape, Low fiber content
N-2-6	T-50 Fiber	Direct strip formation from A201 melt using argon jet opposing slotted roller	Alignment difficult, Low fiber content
N-3-5	T-50 Fiber	Direct strip formation from A201 melt using matched pair of male-female rollers	Alignment difficult, Consistent shape
N-5-7, N-20-3	T-50 Fiber	Direct strip formation from A201 melt using wide rollers with spring tension	Consistent shape, Some alignment difficulties

Table 3

THORNEL 50/Al 201 STRIP PROPERTY SUMMARY SHEET

STRIP-FORMING METHOD	OPEN MELT WIRE	DUAL ARGON JET	ROLLER & ARGON JET	MALE/FEMALE ROLLERS	BN ROLLERS	BN ROLLERS	BN ROLLERS
Experiment No.	N-5-6	N-1-2	N-2-6	N-3-5C	N-5-7	N-5-9	N-20-3
No. of Fibers	11,500	11,500	11,500	11,500	11,500	23,000	11,500
Linear Density (g/cm x 10^{-3})	3.40	4.38	6.49	4.00	4.65	4.90	2.40
Cross-Sectional Area (in^2 x 10^{-4})	2.1	2.58	3.80	2.42	2.8	2.1	1.52
Volume % Fibers	25	20	13.5	21.5	18.4	33.0	32.5
Breaking Load (lb)	198	230	253	180	159	250	178
Tensile Strength (psi)	94,300	88,000	66,600	74,400	56,800	80,600	117,000
Theoretical Tensile Strength (psi) (Rule-of-Mixtures)	82,500	70,000	53,750	73,750	66,000	102,500	100,5[illegible]
Tensile Strength as a Percent of Rule-of-Mixtures	114	125	124	101	86	78	116
Modulus (msi)	21.2	12.3	18.3	13.6	16.9	29.1	21.4

T50/A201 ALUMINUM-GRAPHITE COMPOSITE STRIPS



Al/Gr Composite Strips Using the Listed Direct Strip-Forming Techniques from Left to Right.

1. Two argon jets N-1-2
2. Roller and argon jet N-2-6
3. Male/female rollers N-3-5
4. Dual boron nitride rollers system N-5-7
5. Boron nitride rollers system N-20-3

Figure 4

SINGLE ARGON JET STRIP-FORMING PROCESS

RESOLIDIFICATION OF WIRE

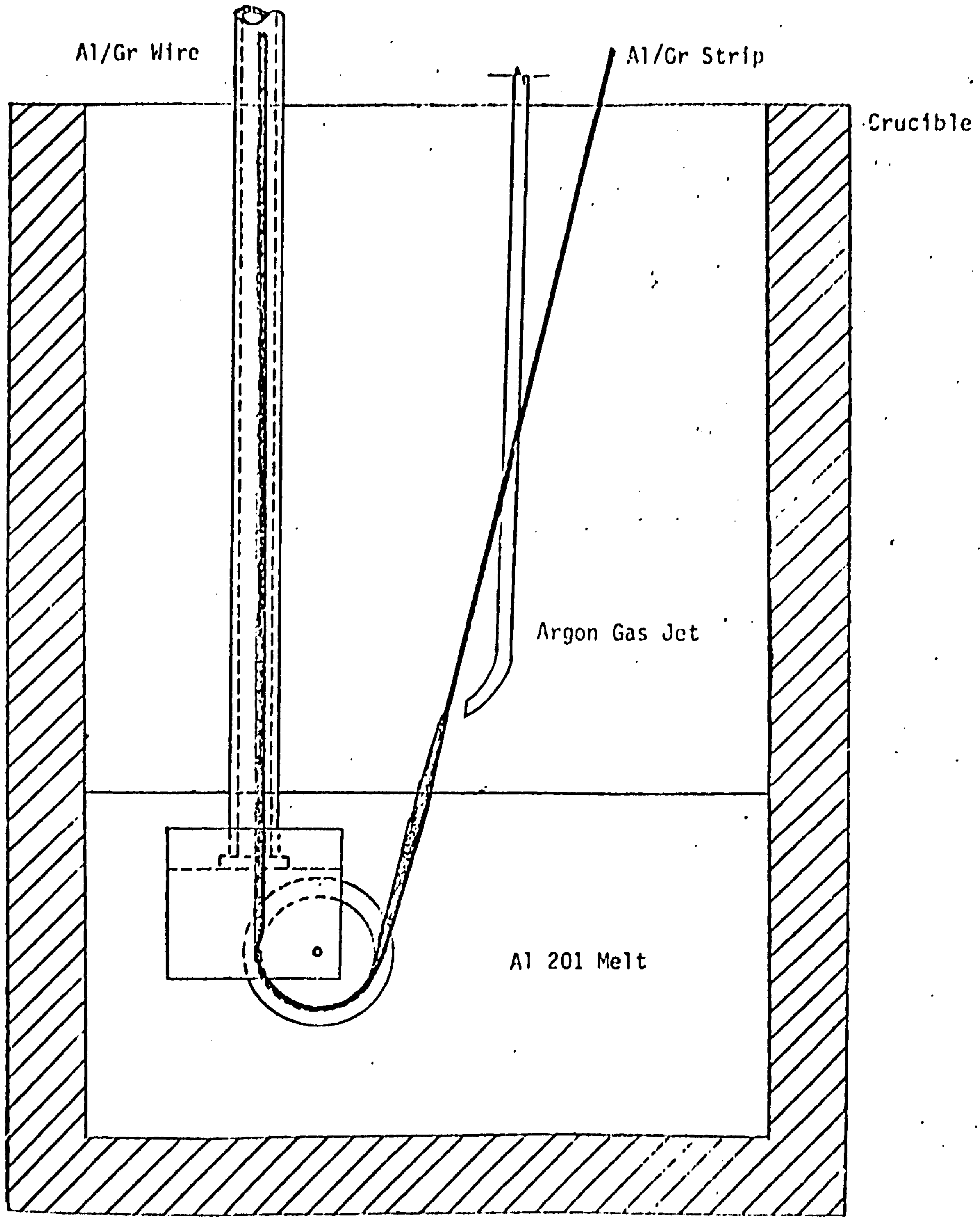


Figure 3

used to shape the wire as it left the melt. Success was obtained in transforming the wire into a strip; however, a high density pure aluminum area developed on the side opposite the argon jet. Results were inconsistent, mainly because alignment between the strip and jet was difficult to maintain. No meaningful test samples were produced by this process.

Modifications of this argon jet process in trial Z-71 eliminated the highly concentrated aluminum areas and also increased the fiber volume fraction. Two argon jets opposing each other and directed downward toward the melt (Figure 4) were used to form the strip from both sides and force the excess aluminum back into the melt. This method did not remedy the alignment problem, however, and the shape again was inconsistent. A second problem encountered in the mentioned processes was a continuous twist occurring in the formed strip, probably caused in part by turns inherently present in the Thornel 50 fiber. Adjustment of the strip drive rollers lessened, but did not eliminate the twisting problem.

Attempts were made to draw a strip through a die during the resolidification of the wire in experiment Z-72. It was felt that a die would eliminate the twisting in the product, and also form a more consistent shape. Irregularities in the wire as it entered the die caused fiber and aluminum to accumulate by the die opening and eventually break the product. This problem coupled with difficulty in finding a suitable material that would withstand oxidation and provide a lubricating type surface at 660°C, made it necessary to seek an alternative method.

By re-melting previously prepared wire during the strip-forming process, the graphite fibers became degraded, and in some instances de-wetted. Due to the strength loss in the strip prepared by this method, it was decided that a direct tape-forming process was necessary using the Lachman Wetting Process and an open melt. That is, an aluminum melt exposed to the atmosphere. In all previous

DUAL ARGON JET STRIP FORMING PROCESS

RESOLIDIFICATION OF WIRE

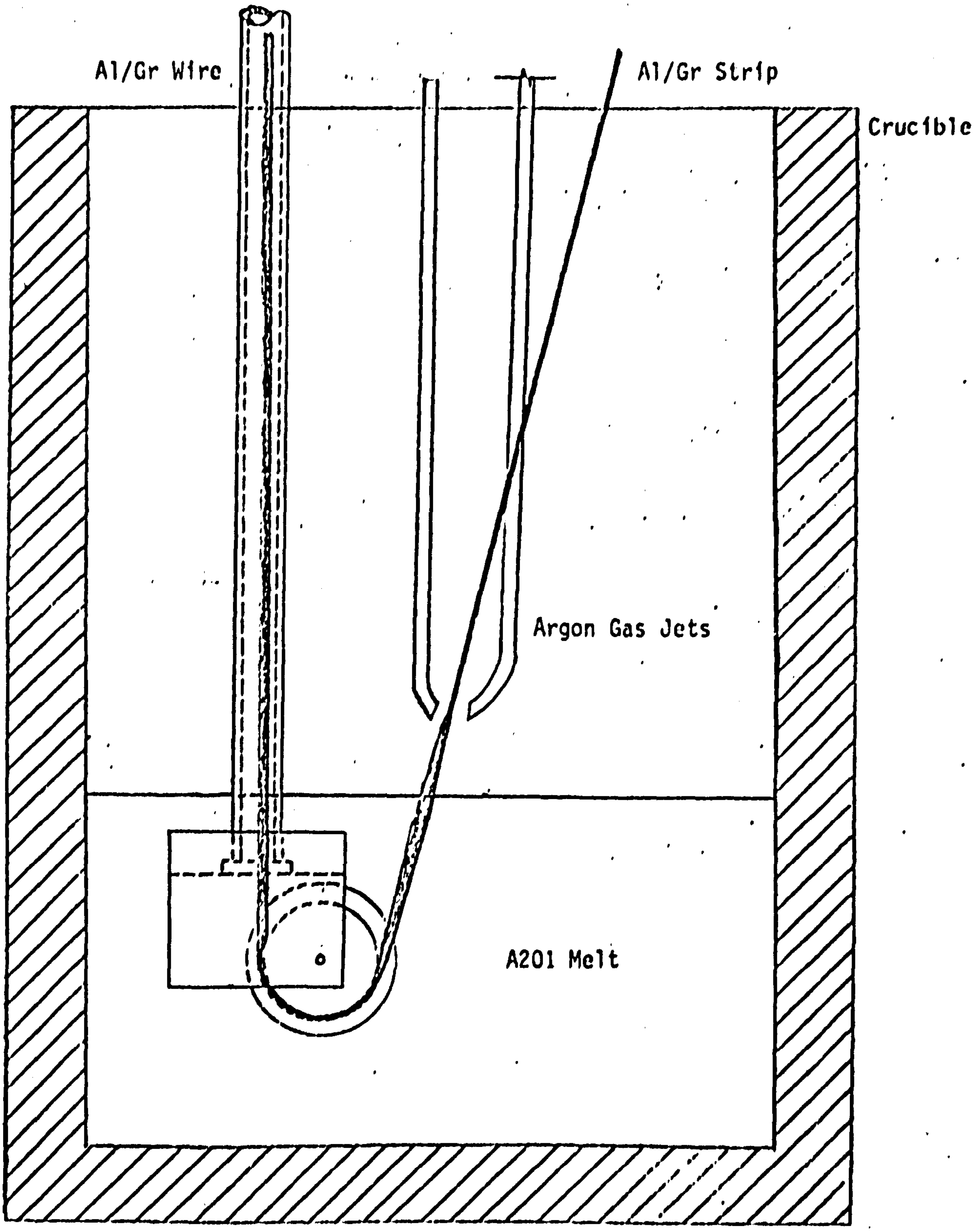


Figure 4

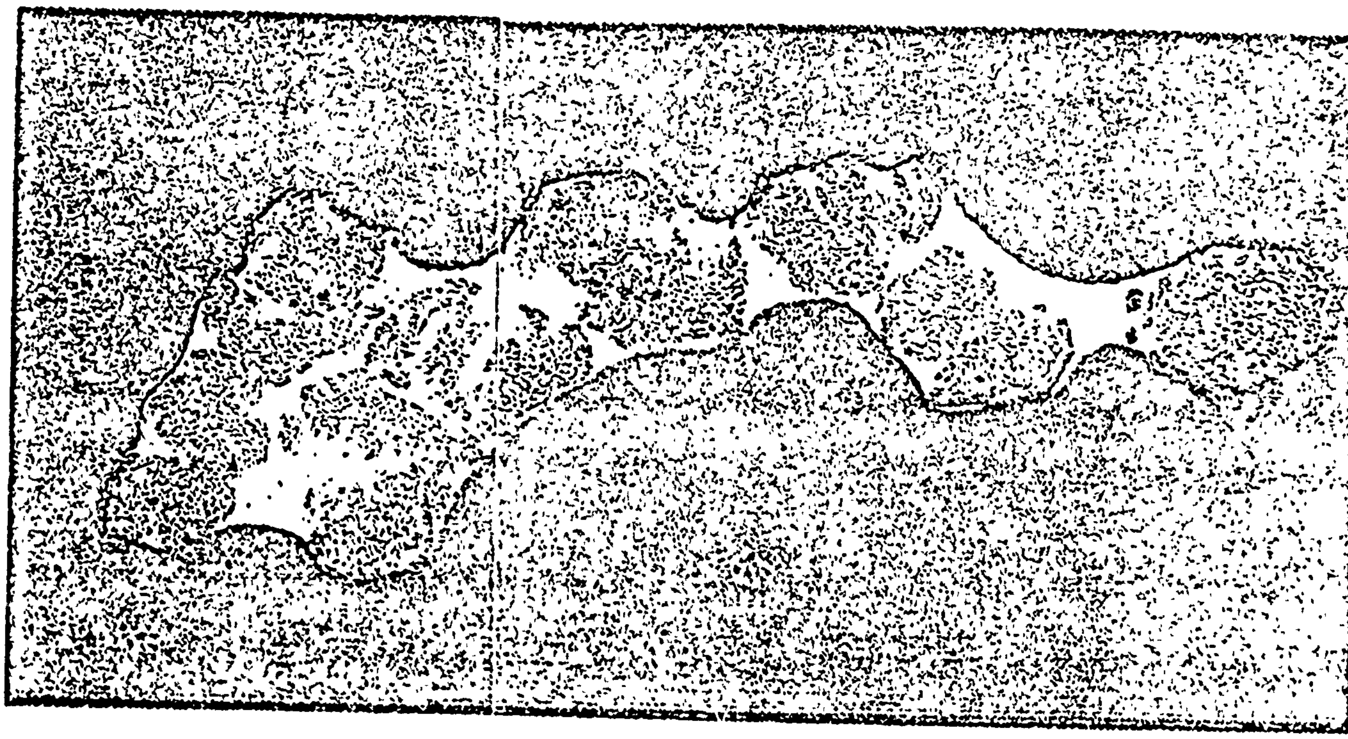
wire-making processes, the aluminum melt was maintained in a closed retort under inert atmospheric conditions to prevent oxidation of the coated fiber and graphite pulley system. Work to make strip from wire as it was directly formed could not be performed in a closed retort because of limited space and poor access preventing necessary adjustments during operation. By opening the melt, it was possible to adjust the position of the shape-forming equipment relative to the melt line and facilitate forming the composite wire into a strip.

Eight strands of T50 fiber were infiltrated for the first time in trial Z-73-8 using an open retort melt with A201 aluminum. Utilizing this new technology, a strip-forming set-up similar to the one used in experiment Z-70 was installed in the infiltration melt and the first direct strip was formed (experiment N-1-2). A photomicrograph of a typical sample produced by this process can be seen in Figure 5.

It became obvious that further improvements in strip-shaping and properties were necessary; therefore, a slotted roller was installed above the melt line and positioned such that the formed composite would travel through the slot. An argon jet was directed downward and perpendicular to the roller maintaining constant pressure on the composite wire. Strip with good alignment of fibers and reasonably consistent width was made using this apparatus in experiment Z-73-14, (Figure 6). Solidification of aluminum and varied pressure on the roller caused non-uniformity in preform thickness, however, as can be seen in Figure 7.

The roller and argon jet were replaced with a male-female graphite pulley system (Figure 8) and improvement in strip geometry was noticeable in material formed during run no. N-3-5C (Figure 9). Aluminum solidification on the rollers was minimized by maintaining a hotter zone directly above the molten aluminum. Constant pressure between the rollers appeared to press out excess aluminum,

T-50/A201 ALUMINUM-GRAPHITE STRIP



Transverse Section 50X

PROPERTIES:

Tensile Strength:	92,000 Psi
Modulus:	12.3 Msi
Number of Fibers:	11,500
v/o Fibers:	20%

Strip-Forming Process: Dual Argon Jet

Figure 5

DIRECT STRIP-FORMING PROCESS

ROLLER-ARGON JET SYSTEM

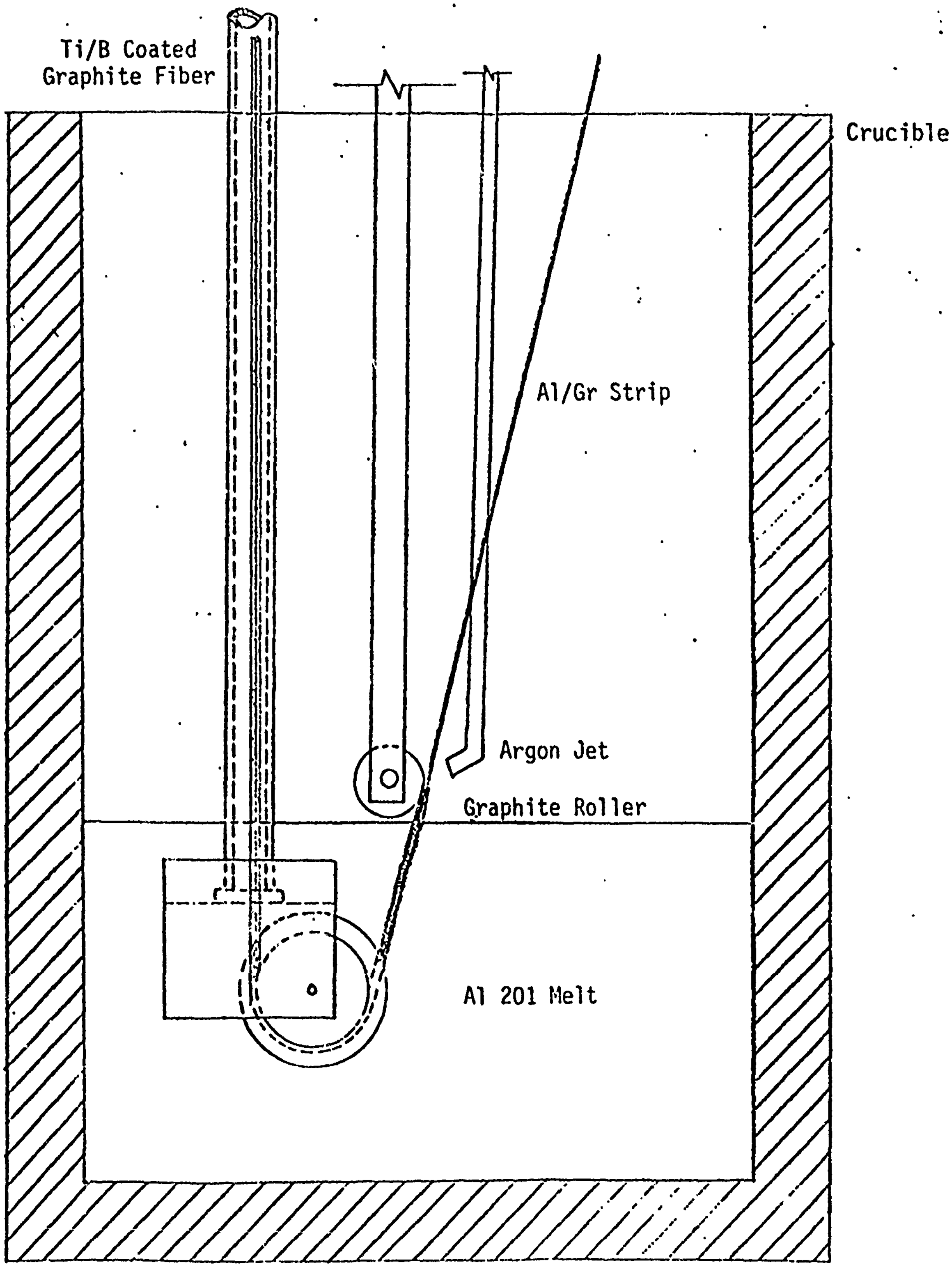
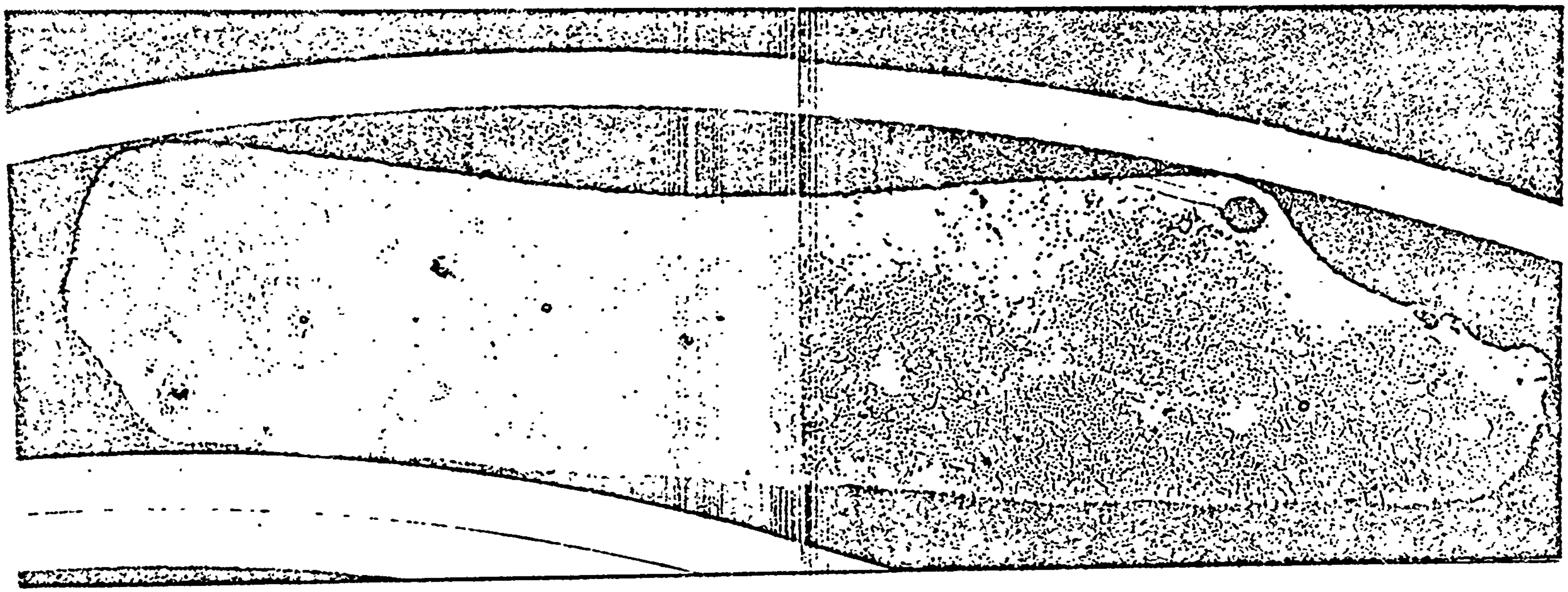


Figure 6

T-50/A201 ALUMINUM-GRAPHITE STRIP



Transverse Section 50X

PROPERTIES:

Tensile Strength:	66,600 Psi
Modulus:	18.3 Msi
Number of Fibers:	11,500
v/o Fibers:	13.5%

Strip-Forming Process: Roller With Opposing Argon Jet

Figure 7

DIRECT STRIP-FORMING PROCESS

MALE/FEMALE ROLLER SYSTEM

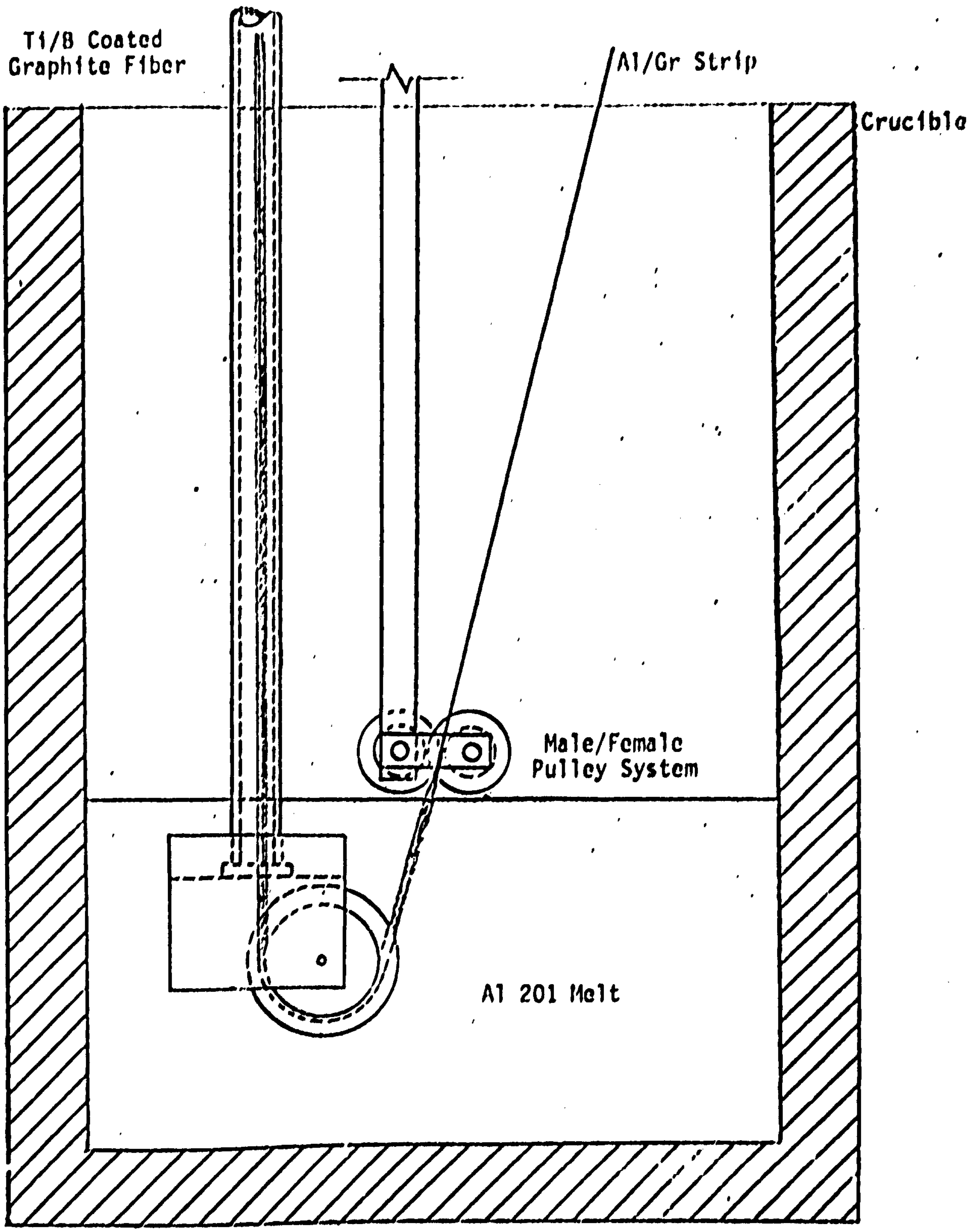
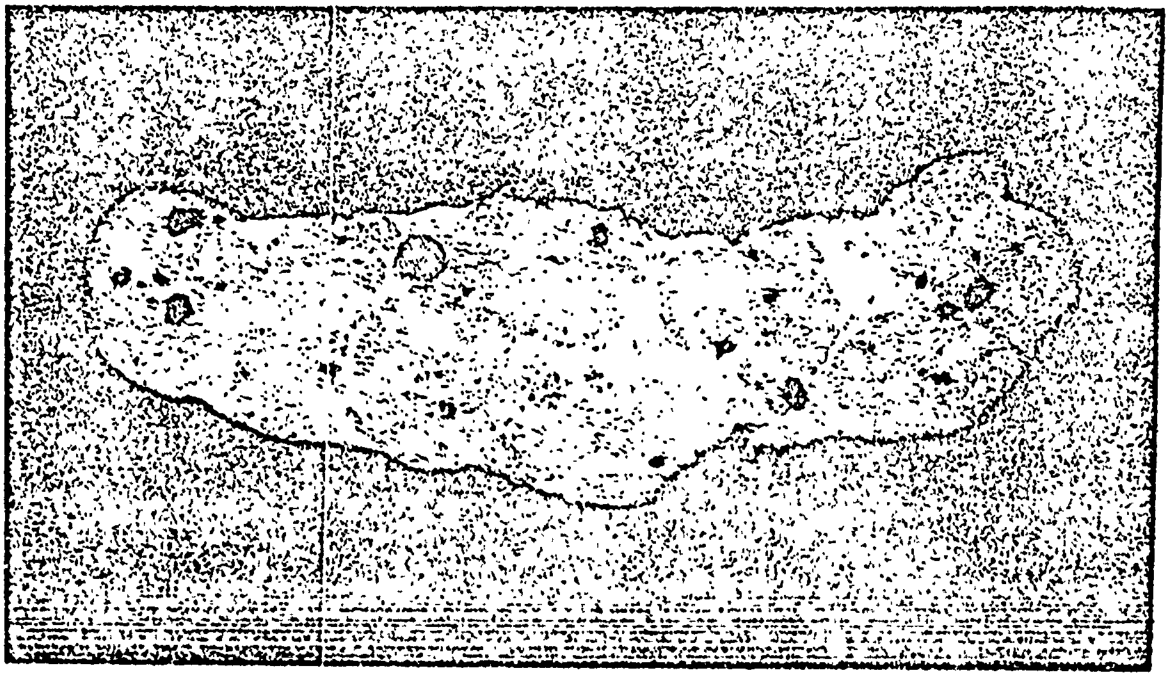


Figure 8

T-50/A201 ALUMINUM-GRAPHITE STRIP



Transverse Section 50X

PROPERTIES:

Tensile Strength:	74,400 Psi
Modulus:	13.6 Msi
Number of Fibers:	11,500
v/o Fibers:	21.5%

Strip-Forming Process: Male-Female Rollers

Figure 9

indicating the possibility of increasing fiber content and shape geometry by increasing this pressure. The delicacy of the graphite rollers due to limited space in the retort, and the problem of oxidation of the graphite prevented these improvements to be made using this system.

A larger melt furnace was designed and the small graphite rollers were replaced with a larger boron nitride roller system (Figure 10). A small groove was machined in one roller to align the strip toward the roll center, and a spring was positioned on the frame to adjust the pressure on the composite. Pressure from the rolls reduced excess aluminum areas and strip in excess of 32 volume percent fibers was formed. Under spring tension, the fibers displayed little sign of degradation, and at the mentioned fiber content, composite tensile strengths exceeded 100,000 psi. Micrographs of strips formed under varied roll tensions can be seen in Figures 11, 12, and 13. A photograph of the actual melt furnace and strip-forming equipment is shown as an insert in Figure 2.

4.2 Testing

4.2.1 Fine Wire Testing

The majority of fine wire testing performed on the aluminum-graphite wire consisted of mechanical property evaluation such as tensile strength, modulus, fiber content, and cross-sectional areas.

The wire specimens for tensile and modulus testing were mounted with fiberglass tabs at a gage length of six inches. The samples were then aligned and positioned in a tensile testing floor model Instron 1115 and pulled to failure at 0.05 inches per minute cross-head speeds. The modulus of the composite was determined by placing a one-inch extensometer on the wire as it was pulled to failure and the slope of the stress-strain relationship was calculated.

DIRECT STRIP-FORMING PROCESS

DUAL BORON NITRIDE ROLLER SYSTEM

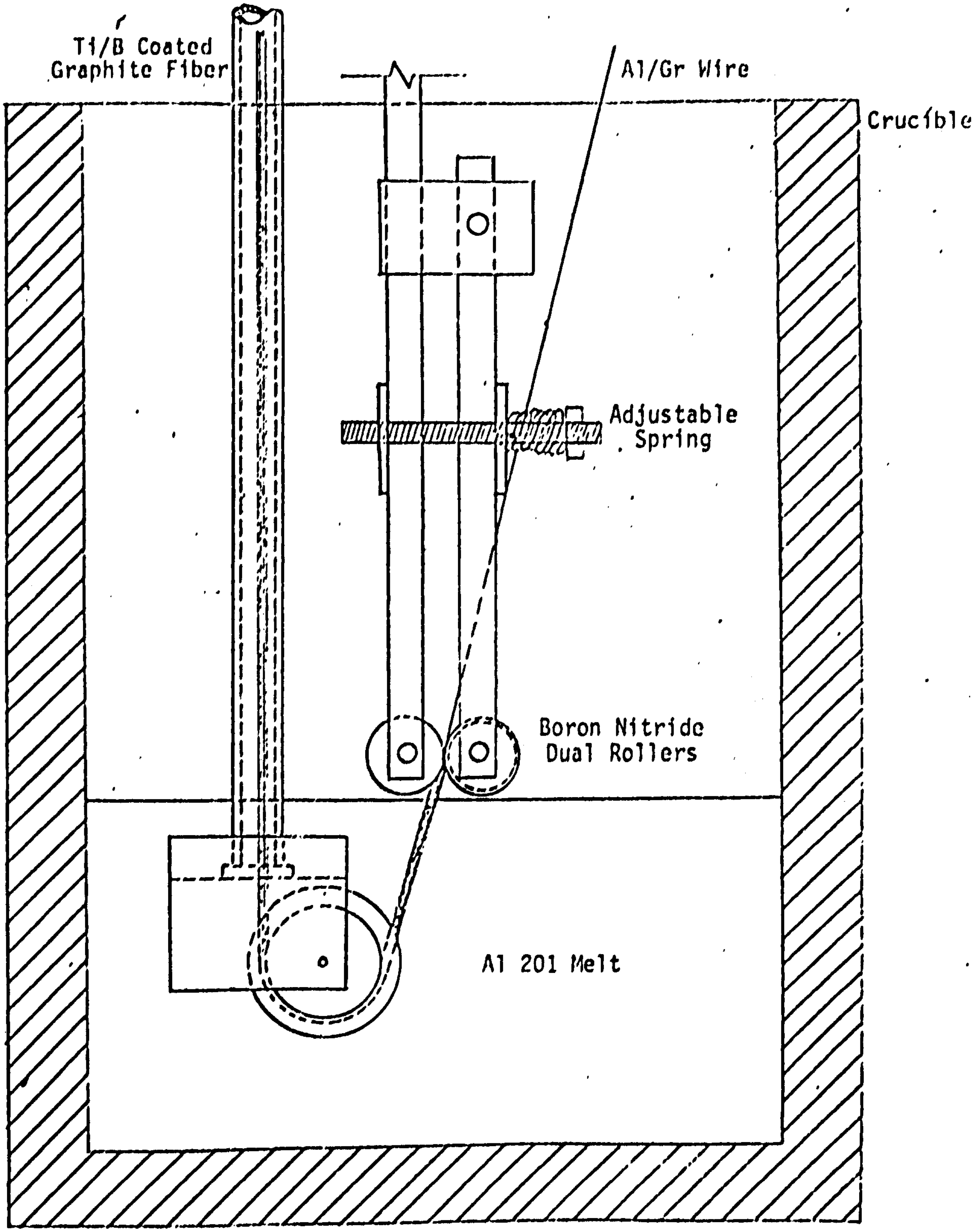
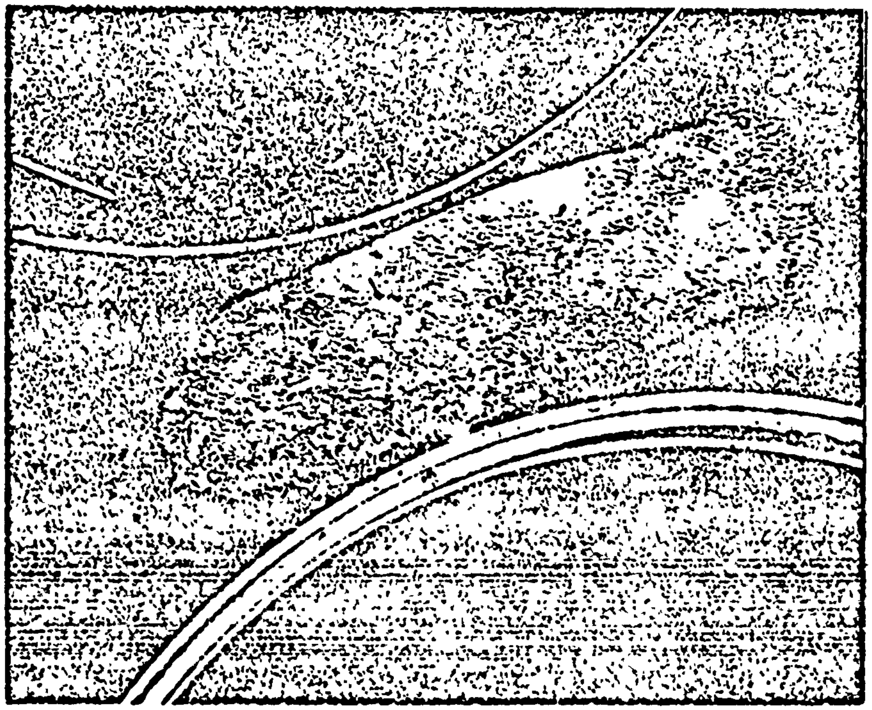


Figure 10

T-50/A201 ALUMINUM-GRAPHITE STRIP



Transverse Section 25X

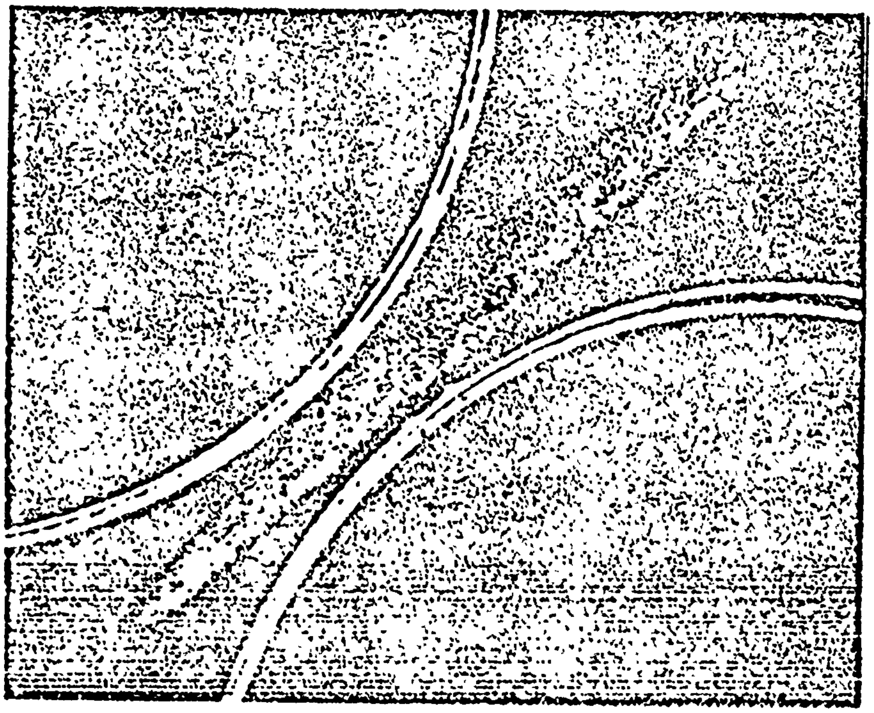
PROPERTIES:

Tensile Strength:	61,300 Psi
Modulus:	19.4 Msi
Number of Fibers:	23,000
v/o Fibers:	18.4%

Strip-Forming Process: Dual Boron Nitride Rollers

Figure 11

T-50/A201 ALUMINUM-GRAPHITE STRIP



Transverse Section 20X

PROPERTIES:

Tensile Strength: 72,600 Psi

Modulus: 27 Msi

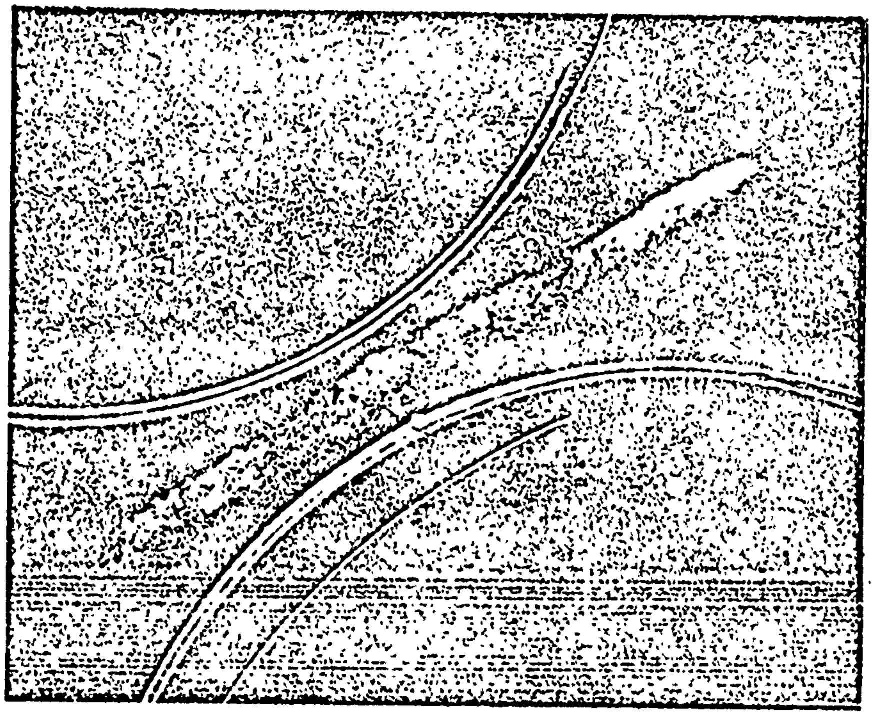
Number of Fibers: 23,000

v/o Fibers: 30%

Strip-Forming Process: Dual Boron Nitride Rollers

Figure 12

T-50/A201 ALUMINUM-GRAPHITE STRIP



Transverse Section 20X

PROPERTIES:

Tensile Strength:	80,600 Psi
Modulus:	29.1 Msi
Number of Fibers:	23,000
v/o Fibers:	33%

Strip-Forming Process: Dual Boron Nitride Rollers

Figure 13

Two analyses were used for determining cross-sectional areas of the fine aluminum-graphite wire. Average area values were obtained from density measurements determined by liquid displacement methods using dichlorobenzene as the liquid medium. These values were verified by measuring areas of transverse micrographs with a planimeter. Practically speaking, both methods gave identical values; therefore, a graphic relationship between cross-sectional area and linear density was established, and used for immediate results during process optimization studies.

A similar graphic relationship was developed for volume percent fibers and linear density, which was compared to fiber fractions obtained by wet chemical analysis. As before, the values obtained from each test method were comparatively equal.

Micrographic preparation of the wire involved mounting, grinding, rough polishing and final polishing for examination and photography. Each mount was impregnated in a clear epoxy resin mixture under atmospheric conditions in an aluminum ring. The hardened surface was then ground by hand on a rotating wheel using a water lubricant and progressing from 320 to 600 grid metallographic polishing paper. Nylon or metcloth positioned on a rotating wheel with one micron diamond paste lubricant was used to rough polish the samples by hand, and final polishing was accomplished using microcloth and a 0.05 micron alumina lubricant. Micrographs of transverse and longitudinal sections for further analysis such as cross-sectional area or dimensional calculations were taken on positive Polaroid black and white film. Specimens are presently on file in the Test Laboratory at FMI.

4.2.2 Strip Testing

Similar methods employed in testing the aluminum-graphite fine wire were

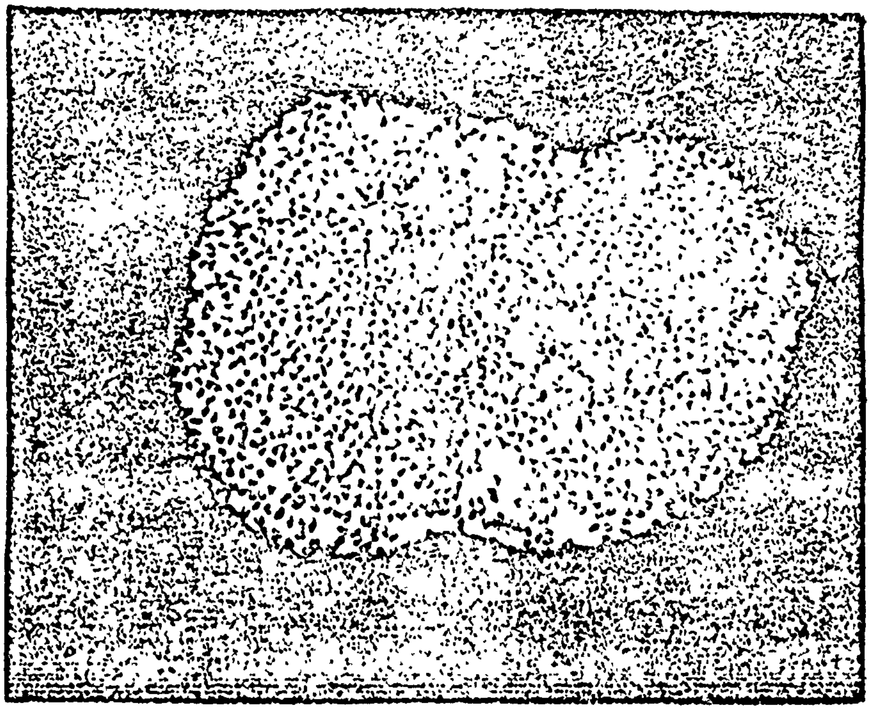
used in evaluating the aluminum-graphite strip. Tensile and modulus properties were generated using, again, a 6-inch gage length between fiberglass tabs. Fiber content, cross-sectional areas, and strip geometry were determined by linear density relationships, liquid displacement, and metallography, respectively.

5. RESULTS:

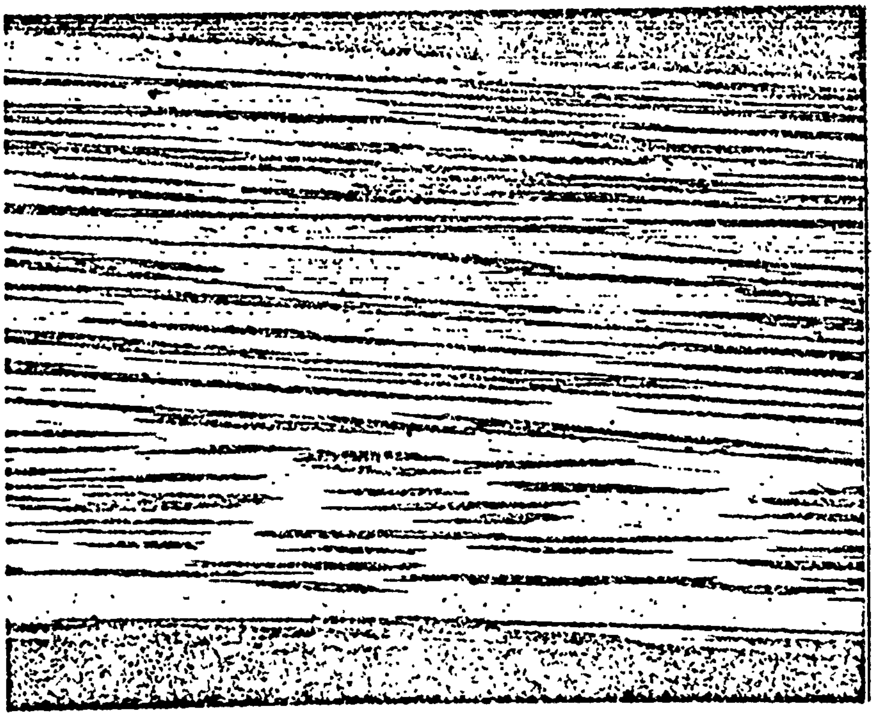
Table 1 demonstrates the improvement obtained in fine wire properties during the first phase of the program. Optimum tensile strengths in excess of 160,000 psi at 41 volume percent fibers were realized at speeds approaching 60 inches per minute. No explanation is offered for the fact that ultimate tensile strengths exceeded rule-of-mixture values. Micrographs of transverse and longitudinal views of the fine wires can be seen in Figure 14.

Difficulty was encountered when the single strand wire was re-melted and joined as a strip during resolidification. Problems such as misalignment of wires, voids, unwetted areas, breakage, and obvious fiber degradation were noticeable. It became evident that re-melting wires would not reproduce a composite with the same excellent wire properties; therefore, a direct strip-forming process was initiated.

The feasibility of directly forming an aluminum-graphite composite strip from the process melt was demonstrated using eight and sixteen strands of Thornel 50 fiber with A201 aluminum, Table 2. Strips with 110,000 psi tensile strength and 21 million modulus at 32+ volume percent fibers were made. The properties were similar to the previously prepared eight strand aluminum-graphite wire values, Table 3. Microstructures of the strips are shown in Figures 5, 7, 9, 11, 12, and 13. Maximum strip size using 23,000 filaments of Thornel 50 was 0.25" x 0.015".



40 $\frac{v}{o}$ fibers Transverse Section 200X



Longitudinal Section 250X

FIGURE 14: Single Strand T-50/A201 Aluminum Graphite Wire

6. DISCUSSION:

Various process improvements were necessary to increase operating speed, fiber content, and ultimate tensile strength of fine aluminum-graphite wire. The handleability of the single strand fiber tow was, for example, a limiting factor in producing the wire at an accelerated rate. Mechanical improvements in the physical plant as well as parameter optimizations within the coating chamber, contributed to an increase in operating speeds from 12" per minute to 60" per minute.

It was observed that by increasing the back tension of the fiber in the yarn box to three pounds, a composite wire of 38 to 43 volume percent fiber was formed. Increases in fiber tension beyond three pounds, however, resulted in fiber handling problems and unwetted fiber areas, while decreases in back tension caused a fall in fiber content. A force of approximately three pounds, therefore, proved to be the optimum operating tension for a maximum fiber density composite wire.

Improvements in tensile strengths were primarily due to temperature control in the aluminum melt. At temperatures above 660°C, the graphite fiber degraded somewhat, probably due to the reaction of carbon with aluminum forming aluminum carbide. Therefore, at temperatures above 660°C, a wire of lower ultimate tensile strength was produced. By maintaining the melt temperature at about 660°C, little to no degradation occurred, and wire strengths exceeding rule-of-mixture values were obtained.

Rule-of-mixture properties were calculated by combining the average bundle strength of 1440 Thornel 50 fibers (measured in tests of fiber tows, impregnated with an epoxy matrix) with the yield strength of the as-cast A201 aluminum alloy (approximately 20,000 psi). The fiber bundle strengths, as reported by NETCO in

"Evaluation of Graphite-Aluminum Composite Materials" Fourth Quarterly Technical Progress Report, July 1974, were about 80% of the individual T50 fiber strengths. These rule-of-mixture values were assumed for both the wire and the strip composites and are included in Tables 2 and 3.

The open melt technology developed during the program became a necessary prerequisite to optimize forming techniques and strip properties. Resolidification of aluminum-graphite wires into a continuous ribbon preform was an ineffective method of obtaining good mechanical properties. The need to directly form strip in the infiltration process melt was realized. Initial experiments attempting to form a strip by drawing previously prepared wire through an aluminum melt and shaping during resolidification did, however, demonstrate that a flat ribbon could be formed directly from the melt.

The initial work in the development of the open melt infiltration system produced a composite with similar properties to the wire made from the closed retort system (Figure 15). This new advancement not only allowed strip-forming equipment to be installed directly over the melt, but it also eliminated a time-consuming problem in the overall process. Using the closed retort system, if a fiber strand either broke or slipped off the retort melt pulley, the time required to correct the situation could take as long as four hours, whereas with the new open melt system repairs are made in a few minutes. A schematic diagram of the open melt set-up can be seen in Figure 16. Several materials were tried in the process of finding a suitable material for an open melting operation that was oxidation resistant and also compatible in aluminum. Graphite, silicon carbide coated graphite, and boron nitride were all used; however, each material had short life spans due to oxidation problems. Oxidized titanium tubing was found to be compatible in the melt, and also sufficiently resistant to attack by

T-50/A201 ALUMINUM-GRAPHITE WIRE

Transverse Section 50X

PROPERTIES:

Tensile Strength:	94,300 Psi
Modulus:	21.2 Msi
Number of Fibers:	11,500
v/o Fibers:	25%

Figure 15

OPEN MELT SET-UP

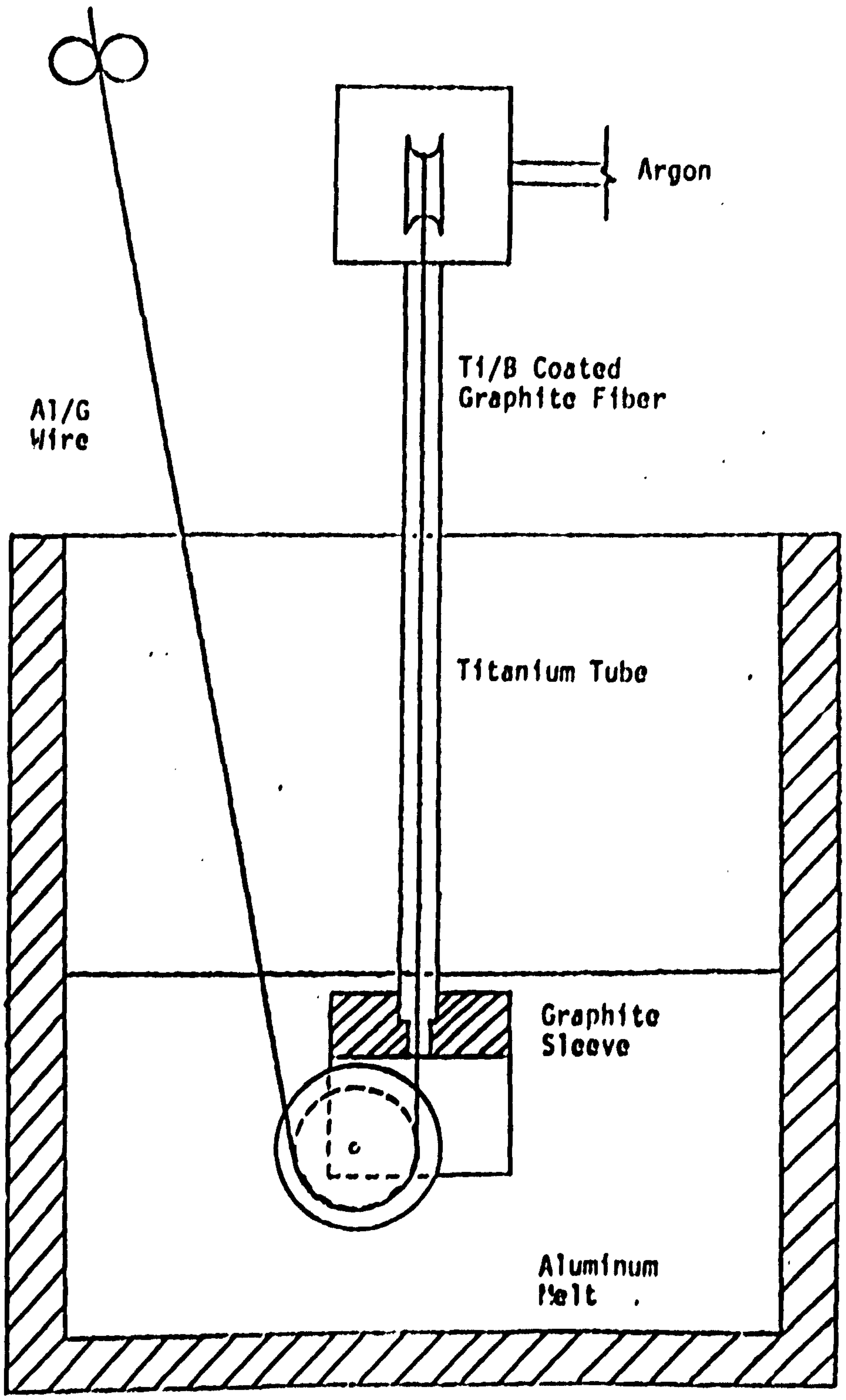


Figure 16

oxygen. This tubing coupled with a graphite pulley submerged in the aluminum proved to be the most durable and least expensive arrangement.

Probably the best way to demonstrate improvements in the strip-forming process during the program is to refer to the property table (Table 3) and the photomicrographs of the transverse sections of these preforms (Figures 5, 7, 9, 11, 12, 13). The evolution of the boron nitride two roller system from the single argon jet arrangement certainly increased the properties and shape of the strip composite. One must carefully view the results in evaluating the manufacturing scale-up possibilities of such a process, however. The transformation from the present R & D demonstration of a 0.25" x 0.015" aluminum-graphite strip into a continuous manufacturing process will incur a significant effort in the process development area.

The program objective of a 0.5" x 0.010" strip with 40 volume percent fibers was not attained due to necessary effort spent on improving the geometry of the actual strip formed and strength properties of the preform. Problems in the system design must be overcome before the process can be utilized to manufacture strip and eventually tapes with consistent physical and mechanical properties.

For example, variances in tensile strengths and geometry were due largely to fiber cross-over or misalignment in the infiltrated strip. Problems in maintaining the free movement of the shaping rollers during continuous operation were caused by binding and occasional slag deposits collecting on the rollers. This contributed to inconsistencies in the preform geometry, strength properties, fiber volume content, and occasional composite breaks at the rollers. Methods of handling larger fiber tows will be necessary if wider strips or tapes are to be prepared with good fiber alignment and high strength and modulus properties.

7. CONCLUSIONS:

Conclusions from the study are:

1. A fine aluminum-graphite wire consisting of strengths in excess of 150,000 at 41 volume percent fibers can be produced for the fabrication of complex shapes requiring a wire with low radius bending ability.

2. Work demonstrates that wire can be shaped in the form of a ribbon or strip directly in the melt following infiltration.

3. A continuous strip-forming process is feasible by coupling strip-forming equipment in an open melt with the Lachman Wetting Process.

4. The strip formation technique using opposing rollers is suitable for the formation of uniform continuous aluminum-graphite strip with no degradation of properties.

8. RECOMMENDATIONS:

More development study is necessary to optimize a process for manufacturing continuous strip and eventually continuous tape directly from a liquid metal infiltrating melt. The need to form a rectangular shape preform for fabrication of complex shapes is an important step in facilitating set-up, increasing fiber packing density, and improving composite properties.

Improvements in the direct tape-forming technique are necessary to insure a consistent geometric shape. Possible solutions include driving the tape-forming rollers to eliminate roller and composite binding, and inserting a knife edge on the rollers to scrape off any aluminum accumulations.

Alignment of the fiber tows must be improved to maintain wire properties in strip preforms. Work must be done in separating the T50 fiber strands possibly by means of a grooved pully sustem, so that each strand is perfectly aligned during the strip formation. Newer fibers without manufacturing twist such as the 6000 and 10,000 filament tow PAN precursor fibers might be amenable to such a strip-forming process.

Handleability of larger tows within the system will lead to wider strip formations and eventual tape formation directly from the infiltrating melt. Development is necessary to align such tows, and also treat them to promote complete liquid metal wetting and prevent fiber degradation. Improvements in fiber volume percent and composite properties must also be included in developing the present feasibility status of a direct strip-forming process to the point where manufacturing scale-up will become possible.

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